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Potential of district cooling in hot and humid climates

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HIGHLIGHTS

- Operation of the large-scale district cooling grid was simulated.
- Proposed district cooling grid reduces CO2 emissions and energy consumption.
- Implementation of DC grid positively impacts the economics of the energy system.
- Singapore was chosen for a case study that represents hot and humid climates.
- The model is well suited for the other countries in the region.

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ABSTRACT

Efficiently utilizing energy that is currently being wasted can significantly increase energy efficiency of the system, as well as reduce the carbon footprint. In hot climates with large cooling demands, excess waste heat can be utilized via absorption chillers to generate cold. Moreover, cold from liquefied natural gas gasification process can further provide energy source for meeting the cold demand. In order to connect the large sources of waste heat and cold energy with customers demanding the cold, a significant investment in district cooling grid is a necessity. In order to deal with the mentioned issue, an existing energy balance model was complemented with Matlab algorithms in order to model the whole energy system, including the detailed representation of the district cooling grid. Singapore was chosen for a case study and several different scenarios were developed for the year 2050, with the main indicators being total primary energy supply, total CO_2 emissions and total socio-economic costs. The most beneficial scenario for the year 2050 had 19.5% lower primary energy demand, 38.4% lower total socio-economic costs and 41.5% lower CO_2 emissions compared to the business-as-usual scenario for the year 2050, although significant investment in the district cooling grid was included in the calculations.

1. Introduction

Climate change is impacting the Earth, posing a threat to sustainable development of different regions. Though agreement was reached during the COP21 [1] and COP22 [2] conferences in Paris and Marrakech, resulting in a now legally binding agreement upon curbing the CO_2 emissions, harmful consequences of climate change cannot be avoided and mitigation measures need to be adopted. Furthermore, rapid urbanization is taking place and it is expected that two thirds of world population will live in cities by the year 2050, increasing the complexity of energy supply [3]. Some regions will urbanize more rapidly than the others, presenting the need to detect the most efficient energy solutions early, in order to avoid a lock-in effect of investing in inefficient infrastructure [4].

Around the tropics, climate is dominated by humid air and high temperatures throughout the year, causing large energy demand for decreasing air temperature and dehumidifying the air [5]. Large and relatively constant energy demand for cooling throughout the year can be met by different sources. Although in more moderate climates heat sinks are better researched, either in terms of free cooling of rivers and lakes or in combination with chillers, there is a lack of possible heat sinks in regions being close to the thermodynamic equilibrium, where the climate is being dominated by small temperature differences of the air, ground and sea during the year [5]. The potential of ground source

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Nomenclature

Term	Remarks, units
WH_i	yearly waste heat potential of the *i*-th considered plant, kWh
η_{total}	total potential efficiency of the plant, kWh_{output}/kWh_{fuel}
$\eta_{electrical}$	electrical efficiency of the plant, kWh_e/kWh_{fuel}
$Fuel_i$	yearly consumed fuel energy in the considered plant, kWh
$C_{supply,LNG}$	cold extracted from LNG gasification process, kWh
LNG	amount of liquefied natural gas imported, kg
$C_{supply,i}$	cold potential of the *i*-th considered plant, kWh
$C_{supply,total}$	total cold potential in the considered area, kWh
A_{cool}	total buildings area that needs to be cooled down,
PR_i	plot ratio of the *i*-th land plot, m^2/m^2
$A_{land,i}$	*i*-th land plot area,
C_{demand}	yearly cooling energy demand per m^2 of the considered area, kWh/m^2
EUI_i	energy use intensity, $kWh/(m^2 * year)$
T_{loss}	thermal losses in the grid, kW
P_{loss}	power needed to overcome the pressure losses in the grid, kW
$E_{supply,t}$	power that needed to be supplied in each hour in order to satisfy the final energy demand in each hour and losses of the transmission and distribution grids, kW
c_p	specific heat of water, 4.187 kJ/(kg K)
U	overall heat transfer coefficient, $W/(m^2 K)$
A	area of the pipe surface,
ΔT_1	temperature difference between the water flowing inside the pipes and the ground on the outer wall of the piping, K
l	length of the considered pipe section, m
r	radius of the pipe section, m
Q	volume flow inside the pipe section, m^3/s
ρ	density of water 1000 kg/m^3
f_D	darcy friction factor, –
v	velocity of the flow, m/s
ΔT_2	temperature difference between supply and return line of the DC network, K
$\dot{m}$	mass flow inside pipe section, kg/s
l_i	length of the each pipe section, m
P_i	price per meter of each pipe section, USD/m

heat pump in western Singapore was assessed in [6]. The main detected benefits were potential reduction of heat island effect by removing cooling towers and reduced water consumption [6]. However, the authors of the paper acknowledged unfavorable ground conditions in Singapore and concluded that the latter is the main reason for relatively low electricity consumption reduction [6]. Bruelisauer et al. analyzed ground, seas, river and air temperatures of Singapore and concluded that they are not suitable sources for free cooling in any of the seasons during the year [5]. Hence, alternative cooling sources need to be selected for meeting the cooling energy needs.

Cooling demand can be met focusing on individual solutions or focusing on one solution for the whole building, cluster of buildings or the whole districts. Individual solutions usually involve air-conditioning split systems, technically called air-to-air heat pumps. In the tropical region, for the general cooling energy needs of buildings, split systems usually achieve coefficient of performance (COP) in the range of 2.5–3.25, electric chillers with dry air cooling tower achieve COP in the range of 3.5–5 and electric chillers with wet cooling tower achieve COP in the range of 6–10 [5].

Compared to individual split systems, more efficient solutions can be done using absorption or electric chillers. An absorption chiller uses waste heat at temperatures around 90–95 °C [7], while electricity is needed only for pumping the working fluid. Therefore, it is possible to expect total plant electrical efficiency ratio (EER) of 15–25, while thermal energy efficiency for single effect absorption units is typically 0.7 [8]. In order to be able to utilize absorption chillers, one must have steadily available streams of waste heat as otherwise electric chillers would be more viable. It was shown that despite the advances of electrically driven chillers, utilization of absorption chillers leads to the cost-effective CO_2 emission reduction, if there is availability of cheap excess heat [9]. Further research on upgrading cogeneration to trigeneration systems was presented in [10]. The authors showed that the trigeneration is beneficial for the northern European countries; however, they have pointed out that it would be very interesting to apply their research to tropical regions, where more steady demand for cooling occurs throughout the year [10].

One of suitable sources for district cooling is liquefied natural gas (LNG) regasification. In an advanced liquefaction process, about 2900 kJ/kg of energy is consumed; 2070 kJ/kg being dissipated as heat and 830 kJ/kg (0.23 kWh/kg of LNG) being stored in LNG as cold [11]. However, due to the cryogenic temperature of LNG, released cold is also suitable for air separation, material freezing, dry ice production and refrigeration in chemical industry. Thus, several solutions can compete for the same resource. According to the available literature, LNG cold from regasification can be utilized for air separation, power generation, cold storage and dry ice production, as well as for district cooling [12]. A very successful example of utilization of cold energy from LNG gasification is a cascade process developed at Osaka LNG terminal [13]. They have combined ethylene plant, air separation, carbon dioxide liquefaction, water chilling and the expansion turbine in order to utilize the cold, achieving exergy efficiency of 52% [13].

In tropics, although there is often a lot of waste heat available from industry and different energy plants, there is usually a lack of demand for it, as the temperatures are high throughout the year. Hence, in hot and humid climates, a district cooling grid is one of the potential solutions for distributing the waste energy in the form of cold to the customers. Although focusing only on municipal waste incineration plants as a potential heat source in tropical urban areas, researchers showed on the case of Thailand that absorption chillers are capable of introducing significant savings in the energy system, by reducing the electricity demand for compression chillers [14].

Most of the past large district cooling research projects, in terms of number of case studies, were carried out or are currently undergoing in Europe, where cooling demand is less steady and highly seasonal in comparison with tropical regions. The most significant project that was finished is the Rescue project [15], funded by the EU. Other important projects are Stratego [16] and International Energy Agency's advocated case study on district cooling in Stockholm [17]. The Rescue report advocates that the first step should be the identification of all possible sources of natural cooling and the second step should be locating the waste heat potential [15]. The Stratego report argued that the optimal level of district cooling is still unclear and recommended more research to be carried out towards the design of the district cooling network [16]. On the other hand, the largest projects on district cooling in terms of capacity took place in Qatar, Kuwait and United Arab Emirates. In Qatar, the district cooling plant at The Pearl-Qatar has the combined cooling power of 450 MW and it seems to be the world's largest integrated district cooling plant so far [18]. In Kuwait, the Shadadiyah University's campus will be cooled with 36 electric chillers with the combined cooling power of 252 MW [19]. However, the latter two projects are lacking of systematic scientific research on the operation of the systems. District cooling system was proposed for the South East Kowloon Development project in Hong Kong and the authors concluded that the proposed district cooling system for the region was feasible, except the cold storage that was not profitable according to the existed financial conditions [20]. The proposed system was later developed and achieved energy savings were 20–35% compared to the air conditioning split systems and decentralized chillers [21]. The designed capacity of 284 MW will result in annual electricity saving of 85 GWh, equivalent to the CO_2 reduction of 59.5 ktons [21].

In Iskandar, Malaysia, a new industrial park is being built in phases. The electricity demand is expected to be met by the combined-cycle gas turbine with the electric output of 45 MW [22]. The pre-feasibility study of the district cooling in the area proposes to utilize waste heat from the gas power plants (PP) to drive absorption chillers in order to provide the cold in the industry park [22]. One of the largest district cooling networks is located in central Singapore and it is cooling the Marina Bay district [23]. The combined chiller capacity of two plants is 157 MW of cooling energy with the possibility to extend the capacity in the coming years [23]. Cold is being produced by electric chillers, while ice thermal storage with the discharge rate of 30 MW is installed to optimize the cold supply. Finally, the authors in [24] mentioned waste heat from different energy plants that could be used for district cooling in the tropical region. However, their proposed "cooling highways" were not their core aim of the research; hence, transmission and distribution grids were not calculated thoroughly and there is a lack of exact quantitative results that could be used for estimation of the pros and cons of large district cooling systems.

The presented literature review shows that the majority of systematic research was carried out in Europe with other climate patterns than in the tropics. Some district cooling projects, focusing on specific energy sources, were carried out in the South-east Asia; however, DC was not researched on a system scale, missing the consequences that DC can have on other energy sectors, such as the power sector. As there is no country in tropical region that has adopted DC on a wide scale so far, there is a need to research the potential of widely adopted DC in regions with steady cooling demand, in order to assess the interactions between different energy sectors, its impact on energy demand and CO_2 emissions. Finally, modeling costs of establishing such systematic networks, as well as dimensioning it, was not the part of any previous research known to the authors.

Thus, in order to address the latter research gap, the aim of this paper is to address the feasibility of utilizing waste heat for cold and LNG cooling sources at a high rate, systematically developing the DC network. Second, comparison of the socio-economic costs of the system with high penetration of DC versus the business-as-usual system is another goal of the paper. Third, existing model for hourly energy balancing should be expanded with more detailed DC algorithms in order to allow for robust dimensioning of the DC network, avoiding potential pitfalls in estimation of DC grid installation costs. Besides the methods adopted, a further novelty in this paper is the choice of case study, i.e., the high population density country, with 100% urbanization rate [25] and with steady cooling energy demand throughout the whole year, as opposed to cases where cooling demand has seasonal patterns and free cooling energy is sometimes available. The latter consideration makes the model suitable for consideration in other tropical regions, too.

The introduction section of this paper is followed by methods section in which detailed explanation of the combination of already existing energy balancing model EnergyPLAN and the Matlab algorithms developed for representing DC grid is provided. Case study and scenario development is the following section that provides a description of the case study used to prove the hypothesis and fill the detected research gaps. Resulting investment in the district cooling grid, thermal and mechanical losses, as well as the socio-economic and environmental findings are presented in the Results section. The paper ends with the discussion section, in which the results are discussed in the holistic manner, and the conclusions section, in which the main quantitative results are clearly stated.

2. Methods

The developed methods consisted of four steps that were carried out in order to achieve robust results:

(1) Locating potential sources of energy and calculating cold potential.
(2) Calculating cooling energy demand of the considered area for utilization of district cooling potential.
(3) Establishing initial grid layout, calculating cold flows, heat and pressure losses in the grid and establishing piping diameters needed to meet the peak cooling energy demand.
(4) Calculating socio-economic costs of different scenarios utilizing district cooling energy and comparison with business-as-usual (BAU) scenario.

2.1. Locating potential sources of energy and calculating cold potential

This step consisted of locating the major gas PPs, waste incineration plants and LNG gasification terminal and estimating the waste heat potential. Waste heat potential was estimated using Eq. (1)

$$WH_i = (\eta_{total} - \eta_{electrical}) \cdot Fuel_i \tag{1}$$

where WH_i presents yearly waste heat potential of the i-th considered plant, η_{total} total potential efficiency of the plant obtained from different references, $\eta_{electrical}$ real electrical efficiency of the plant and $Fuel_i$ yearly consumed fuel energy in the considered plant.

Total efficiency of the plant η_{total} is defined as the ratio of the total useful combined heat and power output and the fuel input, while electrical efficiency $\eta_{electrical}$ is defined as the ratio of the useful power output and the fuel input. Cold derived from LNG gasification was calculated using Eq. (2)

$$C_{supply,LNG} = 0.23 \cdot LNG \tag{2}$$

Recall that the cold content in liquefied natural gas is 0.23 kWh/kg [11], while LNG presents the amount of liquefied natural gas imported [kg]. $C_{supply,LNG}$ presents the cold extracted from LNG gasification process.

Potential cold production, at the locations where waste heat is available, was estimated using the obtained waste heat potentials from Eq. (1) and multiplying it with the COP value of the single phase LiBr-water absorption chillers, as presented in Eq. (3). The most common COP value used in references was 0.7 [7,8,26].

$$C_{supply,i} = WH_i \cdot 0.7 \tag{3}$$

where $C_{supply,i}$ presents cold potential of the i-th considered plant.

$$C_{supply,total} = C_{supply,LNG} + \sum C_{supply,i} \tag{4}$$

In Eq. (4), $C_{supply,total}$ presents the total cold potential in the considered area.

2.2. Calculating cooling energy demand of considered area for utilization of district cooling potential

Initial grid layout should be constructed using the official cadastral plan or master plan or any other similar document. In the cadastral plan, plot ratios are stated for each land plot and area of each land plot can be calculated using different GIS tools. Plot ratio is the ratio of maximally allowed gross floor area (GFA) to land area. Using Eq. (5), the area that needs to be cooled is estimated.

$$A_{cool} = \sum_{i=1}^{n} PR_i \cdot A_{land,i} \tag{5}$$

where A_{cool} is total buildings area that needs to be cooled down, PR_i is plot ratio of the i-th land plot and $A_{land,i}$ is i-th land plot area.

Energy Use Intensity (EUI) in kWh/($m^2 *$ year) for cooling purposes should be extracted from available references and differentiated between the commercial and residential sectors. Using Eq. (6) the final cooling energy demand can be calculated for the considered area.

$$C_{demand} = \sum_{i=1}^{n} PR_i \cdot A_{land,i} \cdot EUI_i \tag{6}$$

where C_{demand} is yearly cooling energy demand per m^2 of the considered area.

2.3. Establishing initial grid layout, calculating cold flows, heat and pressure losses in the grid and establishing piping diameters needed to meet the peak cooling energy demand

The grid layout (transmission and distribution pipes) should be constructed following the layout of the roads as it is considered that this would be economically feasible way for installing DC pipes. Upon initial consideration of the grid layout, mass flows in each piping branch can be calculated taking into account thermal and pressure losses. Results of this part of methods are pipe diameters, needed for the estimation of investment in the DC grid, and losses that occur in the grid, needed to be able to calculate the final delivered energy.

$$E_{supply,t} = C_{demand,t} + T_{loss} + P_{loss} \tag{7}$$

where T_{loss} represents thermal losses in the grid, P_{loss} power needed to overcome the pressure losses in the grid, while $E_{supply,t}$ is cold power that needed to be supplied in each hour in order to satisfy the final energy demand and losses of the transmission and distribution grids.

$$T_{loss} = U \cdot A \cdot \Delta T_1 \tag{8}$$

where U represents overall heat transfer coefficient, A is the area of the pipe surface and ΔT_1 represents temperature difference between the water flowing inside the pipes and ground on the outer wall of the piping. A is calculated using Eq. (9):

$$A = 2 \cdot r \cdot \pi \cdot l \tag{9}$$

where l is the length of the considered pipe section and r radius of the pipe section. The assumption made is one-dimensional heat conduction through the uninsulated pipes. Power needed to overcome the pressure loss is estimated using Eqs. (10) and (11):

$$P_{loss} = Q \cdot \rho \cdot g \cdot f_D \cdot \frac{l}{2 \cdot r} \cdot \frac{v^2}{2g} \tag{10}$$

where Q is the volume flow rate inside the pipe section, ρ density of water, f_D Darcy friction factor and v velocity of the flow.

$$Q = v \cdot r^2 \cdot \pi \tag{11}$$

Cold power needed to meet final energy demand, as well as to overcome the losses in the grid, can also be expressed using Eq. (12):

$$E_{supply,t} = \dot{m} \cdot c_p \cdot \Delta T_2 \tag{12}$$

where ΔT_2 represents temperature difference between supply and return line of the DC network, while mass flow rate $\dot{m}$ can be expressed using Eq. (13):

$$\dot{m} = \rho \cdot v \cdot r^2 \cdot \pi \tag{13}$$

By combining Eqs. (7)–(13) and restructuring the terms, the quadratic equation can be obtained:

$$r^2(\rho \cdot v \cdot \pi) - r\left(2 \cdot U \cdot \pi \cdot l \cdot \Delta T_1 + v^3 \cdot \pi \cdot \rho \cdot f_D \cdot \frac{l}{4}\right) - C_{demand} = 0 \tag{14}$$

In Eq. (14), only radius r of the each pipe section is unknown, while other terms were predetermined using the values obtained from the literature.

$$Cost = \sum_{i=1}^{n} l_i \cdot P_i \tag{15}$$

The total cost of the DC grid is represented by Eq. (15), where l_i represents the length of the each pipe section and P_i the price per meter of each pipe section. It is of utmost importance to bear in mind that P_i depends on the piping radius.

2.4. Calculating socio-economic costs of different scenarios utilizing district cooling energy and comparison with business-as-usual (BAU) scenario

The cost of the district cooling grid calculated from Eq. (15) was input for the EnergyPLAN model. The latter modeling tool was used in order to model the systematic effects that district cooling has on the whole energy system. EnergyPLAN is a simulation tool that is used for modeling energy systems, especially suitable for modeling systems with high share of the intermittent power, as it simulates the energy system during one year on hourly resolution [27]. It follows the concept of smart energy systems, in which synergies detected between power, heat/cold, gas and mobility sectors are utilized in order to develop cheaper sustainable energy system. The detailed comparison between TIMES/MARKAL optimization family of models and EnergyPLAN simulation tool was carried out in [28], while comparison of numerous different energy modeling tools, with the emphasize on those suitable for modeling the renewable energy systems, was presented in [29]. A detailed description of the pros and cons of the EnergyPLAN model was carried out in [30]. The EnergyPLAN model was used for many case studies with the large share of renewable energy systems on different geographical scales. It was used for modeling: regions, such as EU28 [31], countries, such as Ireland [32], cities, such as Copenhagen [33] and islands, such as Mljet [34].

Outputs of the EnergyPLAN model are total energy system costs including fixed, variable and levelized investment costs, CO_2 emissions, primary energy supply,[1] hourly generation of each modeled technology during the year, storage balances, etc.

For the purpose of this model, socio-economic costs included levelized investment costs during the lifetime of each modeled technology, fixed and variable operating and maintenance costs (O & M), fuel costs and new infrastructure costs such as an investment in district cooling grid. They were calculated using Eqs. (16) and (17) [27].

$$Cost = \sum_{i=1}^{n} (fixO\&M_i + lev_{inv_i})x_i + \sum_{j=1}^{m} \left(varO\&M_j + \frac{fuel_j}{\eta_j} + CO2_j \cdot CO2_{inten_j} \right) x_j \tag{16}$$

where

$$levinv_i = inv_i \cdot \frac{disrate_i}{1-(1+disrate_i)^{-lifetime_i}} \tag{17}$$

where $fixO\&M_i$ represents fixed O & M cost (USD/MW), lev_{inv_i} annualized investment cost of a specific technology (USD/MW), inv_i total investment cost (USD), $disrate_i$ real discount rate (%), $lifetime_i$ expected lifetime of the plant (years), $varO\&M_j$ variable O & M cost (USD/MWh), $fuel_j$ and η_j fuel consumption (MWh) and efficiency of the specific technology (MWh/MWh), while $CO2_j$ and $CO2_{inten_j}$ represent the cost of CO_2 emissions (USD/tCO_2) and CO_2 intensity of a specific technology (tCO_2/MWh). Finally, x_i present capacity variables of different technologies i (MW), while x_j represents generation variables (MWh) of those technologies. All the economic values are in real terms, meaning that they are inflation-adjusted during the future years.

Opposite to the business-economic costs, socio-economic costs do not incorporate taxes as they are considered to be internally redistributed income (within the area). On the other hand, the CO_2 tax is not

[1] Primary energy supply (equal to the primary energy demand) is defined as the total energy supply/demand in its crude form, without being subjected to any conversion process.

Table 1
Overview of different scenarios.

	Reference scenario (REF)	Business as usual (BAU)	District cooling (DC)	District cooling and increased PV penetration (DC-PV)	Increased PV penetration (PV)
Year	2014	2050			
Features	Developed using official statistics from different sources	Scenarios representing normal development of the system with no major incentives for change	BAU + the implementation of district cooling system	BAU + DC + rapid penetration of PV systems	BAU + rapid penetration of PV systems

a classical "business tax" as it represents internalized negative externality in terms of climate change costs. Hence, carbon tax was included in the total socio-economic costs.

3. Case study and scenario development

In order to validate the developed model and to assess the impact of district cooling on the holistically modeled energy system, a case study that represents the hot and humid climate was carried out. Singapore was chosen for a case study. Singapore is located only 142 km north from equator and thus it can successfully represent a tropical region. It is also economically developed country with high cooling energy demand. Finally, the large amount of data available to model the energy system, as well as the availability of future plans, makes it suitable for developing the robust case study.

3.1. Overview of the case study and scenarios

Singapore is a 100% urbanized country [25], located in the tropical region in South-east Asia. It has a population of 5.54 million, covering the land area of only 719 km^2. It has a tropical climate, with steady high temperatures, with outdoor temperatures ranging from 24.5 °C to 31.2 °C during the year [35]. According to the World Bank, in 2015 it had GDP at power purchase parity of 80,192 USD in constant 2011 prices, the 3rd highest in the world [36].

Currently, Singapore is producing more than 95% of her electricity from imported gas [37]. In 2014, 337,372 TJ of natural gas and 94,588 TJ of LNG were imported [37]. Thus, the share of LNG in total gas consumption was 21.9% and it is expected to rise in the coming years. Its regasification terminal is located in the south west of the country, having the capacity of around 3 million tons of LNG per annum.

Possible major sources of waste heat in Singapore can be found in industry, especially petrochemical industry [8], waste incineration plants and gas-driven power plants (PPs). There are four operating gas PPs in Singapore, all of them being located on Jurong island in the south west of the country. Two of them utilize waste heat and feed it to the industry in the form of steam. Moreover, most of the electricity that is not produced from gas PPs is generated from waste incineration plants. Currently, there are four waste incineration plants, three of them being located in the Tuas (south-west part of the country) and one of them in the north of the country in the Woodlands district. Presently, they are only generating electricity and they are not using waste heat for any process. Highly efficient combined cycle gas PPs can have electrical efficiency of 60% [38], while total heat utilization of the waste incineration plant in Malaysia was reported at 80% [39]. Combining the data with the reported efficiencies of the Danish technological report [40] shows that a significant amount of waste heat can be utilized from these plants. Although significant amount of waste heat from energy plants is not being utilized currently in Singapore, one can note that all the waste heat comes from several highly concentrated sources.

Concerning the EUI, the value of 215 kWh/m^2 per annum for the commercial sector and the value of 55 kWh/m^2 per annum for the residential sector was adopted [41,42]. The carbon tax in Singapore should start from the 2019 and it is expected to be in the range of 7.15–14.3 USD/tCO_2 [43]. The European Commission issued a report stating expected increase in the CO_2 emission allowances in the EU until the year 2050 [44]. Using the same relative increase in CO_2 price as EU assumed, and the starting price of 10.7 USD/tCO_2 for the year 2019, a carbon tax of 65 USD/tCO_2 was obtained for the year 2050.

EnergyPLAN model was used for developing all the scenarios; reference one for the year 2014 and four scenarios for the year 2050: business-as-usual (BAU), district cooling (DC), district cooling and increased photovoltaics (DC-PV) and increased photovoltaics with no district cooling (PV). The overview of different scenarios can be seen in Table 1.

3.2. Reference scenario

In order to validate the model, a reference scenario (REF) for the year 2014 was developed. Energy supply and demand data were obtained from the International Energy Agency [45] and Singapore's Energy Market Authority [37]. Final energy demand is divided into three sectors in EnergyPLAN: Individual, Industry and Transport, while electricity demand distribution is common and encompasses electricity consumption in all the sectors except electrified mobility. Final energy demand data used for the reference year can be seen in Table 2.

There are currently four gas driven PPs operating in Singapore, all being located on Jurong Island. Furthermore, there are four waste incineration plants, three being located in Tuas area and one in Woodlands area. Total capacities can be seen in Table 3.

As Singapore is geographically constrained and has only limited energy resources, it imported a significant amount of fuels to meet its needs in 2014. It imported 162 Mtoe of energy products in 2014, mostly crude oil and petroleum products, and exported 86 Mtoe of energy products, mostly petroleum products due to its strong refining sector [37]. Total import of natural gas was 10.3 Mtoe, 22% in the form of liquefied natural gas and the rest via the gas pipeline [37]. More than 95% of electricity was generated from gas PPs, while the major share of

Table 2
Final energy demand in the reference year.

Name	2014 [TWh]	Ref.
Electricity demand	49.31	[45]
Individual heating demand	2.81	[45]
Industry fuel demand	69.77	[45]
Transport fuel demand	25.31	[45]

Table 3
Energy supply of Singapore in the reference scenario.

Plant type	Capacity [MW]	Fuel	Efficiency	Refs.
Power plants	2225	Natural gas/LNG	47.5%	[37,46]
Waste-to-energy plants	256.8	Waste	16.7%	[37,45,46]
PV	33.1	–	12.4% (capacity factor)	[37,45]

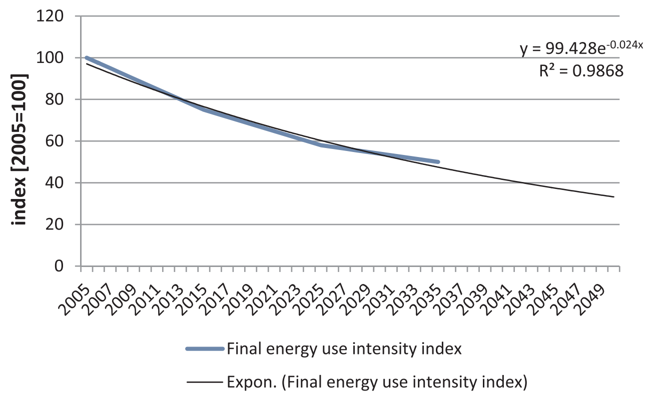

Fig. 1. Final energy use intensity index - projected values (2005 = 100).

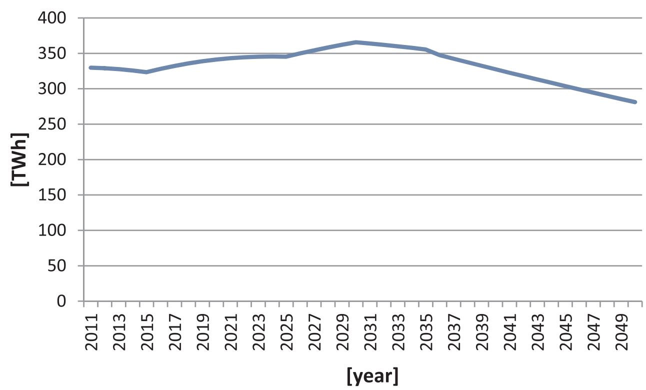

Fig. 2. Total primary energy demand projection.

the remaining part of the power generation had waste incineration plants [37].

According to the IEA's statistics, the total primary energy supply was 28.01 Mtoe, while CO_2 emissions were 45.32 Mt. Hourly electricity demand distribution was obtained from Singapore's Energy Market Authority, while the hourly solar irradiation was obtained from Meteonorm software. Hourly cooling load profiles were obtained from [47,48] and scaled according to the share of each building type's energy consumption [37].

3.3. Business-as-usual scenario

Business-as-usual (BAU) scenario was made for the year 2050. It includes only general policies and economic development without adopting any measures that could boost development of certain technologies or energy sectors. Singapore's population is projected to be 6,680,000 in 2050 [49], while nominal GDP is projected to be 526.1 billion 2010 USD [50]. Singapore's energy intensity up to 2035 was projected in [51] while the energy intensity in 2050 was obtained extrapolating the historical data and projection up until 2035. The obtained energy intensity time series can be seen in Fig. 1.

Combining the population growth data, GDP forecast and energy intensity index, one can obtain total primary energy demand projection up to the year 2050, as presented in Fig. 2.

Thus, the total primary energy supply in the BAU scenario for the year 2050 was estimated to be 281.1 TWh. The share of energy sector consumption to the total energy consumption was modeled to be at the same level as in the reference year. Hence, the total primary energy supply of the energy sector (i.e. consumption that is modeled in EnergyPLAN) was 174.1 TWh in the BAU scenario.

The amount of cold energy available from the LNG gasification terminal was calculated using the Singapore's statistics on LNG imports [37]. Furthermore, it was taken into account that the annual average growth rate of LNG import between 2016 and 2025 is expected to be 10.39% [52], as well as that the total capacity of gasification terminal is expected to be 9 million tons per annum [53]. In order to calculate the cold potential from gasification for the year 2050, the same average yearly growth rate was extrapolated until the year 2030, after which it was held constant. If the demand for gas in the energy system in specific scenario was lower than the capacity of the gasification terminal, the total demand for gas was used as the amount of LNG import in a specific year. For the year 2050, it was assumed that all the natural gas consumed was imported in the form of LNG.

In order to successfully represent a district cooling system and all its interactions with other parts of energy system, it is important to properly model developments of different energy sectors. For the purpose of this paper, most of the expected policies in other sectors were obtained from the official technology roadmaps carried out for CCS, PVs, Green Data Centers, Building Energy Efficiency, Industry Energy Efficiency, Waste Management and E-Mobility. Different research pathways were presented for research, development, demonstration and deployment of the specific technologies. Sector data that were taken from these studies encompasses PV penetration, electric vehicles penetration, expected energy efficiency measures in buildings, industry and power sector [54–57] and the exact figures are presented in Table 4. More specifically, Solar Photovoltaic Roadmap for Singapore presented two main scenarios for future development of PVs in Singapore, the Baseline scenario (BAS) and Accelerated scenario (ACC). The accelerated scenario assumed larger utilization areas for PVs, accelerated growth in PV efficiency and yield and accelerated cost reduction of the technology [54]. Industry Energy Efficiency Technology Roadmap showed a great potential for energy efficiency gains until the year 2030. It assessed five key areas and the technical potential of energy efficiency gains was 5.7% until the year 2030, while additional 13.1% of energy savings could be achieved if best available technologies would be deployed [55]. Electro mobility roadmap presented three different electrification scenario of the transport sector. One of the conclusions claims that in the High Scenario, EVs could bring down emissions from the transport sector by 64% compared to the BAU in 2050 [56]. Furthermore, the roadmap presented for potential scenarios for regulated increase of the number of vehicles, dubbed S1–S4 [56]. In the most beneficial scenario (S4), the number of vehicles in the year 2050 will be the same as in the year 2020 and increase by 2.7% from 2015 to 2020, while in the least beneficial scenario (S1) the number of vehicles in the year 2050 will be 9.1% larger than in the year 2015 [56]. Finally, Building Energy Efficiency R & D Roadmap formulated a list of 52 technologies that need to be developed in order to significantly contribute to the increased energy efficiency in Singapore's building sector [57]. It was calculated that the latter sector alone could cumulatively reduce 22–28% of CO_2 emissions until the year 2030 compared to the BAU scenario [57]. All the roadmaps are freely available on Singapore's National Climate Change Secretariat's website [58].

Furthermore, it was assumed that 90% of the electric vehicles will be connected to Smart Charge system and 10% to Dumb Charge system by the year 2050 (all scenarios) in order to alleviate potentially high peak demands in certain periods of time. Smart Charge system corresponds to the charging according to the present power source and demand situation in the system. Utilizing this option, the system aims for finding the cheapest way of charging the vehicles; e.g., when excess electricity from intermittent sources is available. On the other hand, dumb charge corresponds to the uncontrolled charging of the vehicles straight upon the plug-in of the vehicles.

3.4. Alternative scenarios

Alternative scenarios for the year 2050 include PV, DC and DC-PV scenarios, as described in Table 1. In DC and DC-PV scenarios, district cooling demand, being able to cover all the losses occurred in the distribution grid, was calculated using Eq. (7), while cooling demand was estimated using Eq. (6). Locations chosen to be suitable for a shift towards district cooling were those that are closer to the waste heat sources. Although there are not many references in the literature for the maximum distance of cold supply, there are examples of operating district heating systems with distances of 20 km, such as in Hamburg, Germany, or 30 km, which is the case between Roskilde and Copenhagen, Denmark [63]. As the temperature difference between cooling medium flowing inside the piping and the surrounding ground temperature, and accompanied energy losses, is much smaller in district cooling grids than in district heating grids, at least the same distances should be feasible in the case of district cooling. The furthest point of cold delivery of the district cooling grid from energy sources in this case study was approximately 20 km.

Geographic Information Systems (GIS) mapping of the transmission and distribution piping was determined using the URA SPACE integrated map portal [64]. Plot ratios were taken from Singapore's 2014 master plan [65]. Detailed representation of the proposed transmission and distribution sections used in calculations are graphically represented in Appendix 1. Overview of the data presented in Appendix 1 can be seen in Table 5.

One can notice that proposed district cooling system in the South-west part of Singapore would be significantly larger than in the Northern part as a consequence of larger energy supply for cold generation being available in the South-west part.

Major sources of potential waste heat, as well as LNG gasification terminal can be seen in Fig. 3.

Potential capacity of the PV systems in PV and DC-PV scenarios was calculated updating the assumptions found in the Solar roadmap for Singapore [54]. The authors of the roadmap stated that they have used very conservative estimations of the available area for PV installation. Using less conservative estimations and taking into account the fact that many cooling towers for electric chillers on the rooftops can be avoided using the district cooling system, a net usable area for PV installations was estimated to be 74.4 km^2, as it can be seen in Table 6.

Finally, fuel prices projections for the year 2050 were taken from the US Energy Information Administration [66]. The majority of the technology capital costs, variable and fixed operating and maintenance costs were taken from [27], while the exceptions were PV costs, taken from [54], and DC infrastructure costs, taken from [67].

Table 5
Summary of the data presented in Appendix 1.

	Total transmission piping length [km]	Total distribution piping length [km]	Total floor area to be cooled [km^2]
Woodlands (Northern part)	1.34	4.68	3.64
South-west part	78.69	91.3	146.4

4. Results

4.1. Investment, dimensioning and the operational consideration of district cooling grid

Cooling energy generation was simulated during one week in June and the total cooling energy demand and cooling energy supply, as well as the total investment in infrastructure can be seen in Table 7. Northern and South-west part of Singapore were modeled for cold demand, as it can be seen from Fig. 3 that these geographical areas are the closest to the potential major waste heat and LNG cold sources. Hence, in these areas the installation costs of the transmission and distribution networks will be the lowest.

As Singapore has steady weekly cold demand throughout the whole year, the yearly cooling demand values were calculated by multiplication of the values obtained for the simulated week with the number of weeks in a year.

Initial grid layout was constructed using the official cadastral plan (called the master plan) of the Singapore's Urban Redevelopment Authority (URA) [68]. In the cadastral plan, plot ratios are stated for each land plot and areas of each land plot were calculated using available website tools. Plot ratio is the ratio of maximally allowed gross floor area (GFA) to land area. Calculated cold supply potential C_{supply} in the South-west part includes potential from two out of four gas

Table 4
Adopted figures in different scenarios developed for the year 2050 and corresponding references.

	Statement from the reference	BAU	DC	DC-PV	PV	Ref.
Electric vehicles penetration	Different scenarios; "High" scenario from the [56] assumes that 54% could be BEVs and 12% PHEVs in the year 2050	40% of the total energy demand for transport	63%[a] of the total energy demand for transport	63%[a] of transport energy demand	63%[a] of transport energy demand	[56]
Efficiency in transportation	S4 scenario from [56] – 0.25% vehicle population increase till 2020, 0% afterwards (till 2050)	0.25% vehicle population increase till 2020, 0% afterwards (till 2050)				[56]
PV penetration	15 TWh in the accelerated scenario 7 TWh in the baseline scenario	7 TWh	14.7 TWh	32 TWh	32 TWh	[54]
Energy efficiency in power sector	E3 scenario from [54] would mean 50 TWh of final energy demand for electricity due to the strong energy efficiency efforts	50 TWh of final energy demand for electricity[b]				[54]
PV technological development	PV η = 28%[c] technical lifetime = 40 yearsfull cost (baseline sc) = 0.70 USD/W[d]	Adopted statements from the reference without alterations				[54]
Energy efficiency in buildings	Efficiency measures reflected in final energy demand for electricity that equals 50 TWh					[57]
Energy efficiency in industry	Efficiency measures reflected in final energy demand for electricity that equals 50 TWh; In DC, DC-PV and PV scenarios all coal consumption and 75% of oil consumption is shifted to natural gas consumption by the year 2050					[55]

[a] Assumption derived from the "high" scenario in Ref. [56] for the year 2050.
[b] This number does not include possible further reduction in demand for electricity due to the switch from electric heat pumps to district cooling.
[c] The possible PV efficiency development was also assessed in [59]. The reported expected efficiency for mono-crystalline photovoltaic cell for the year 2027 was 26%.
[d] Relatively low cost assumed for the target year 2050 can also be found in [60], where a discussion on PV price was carried out and the price of 0.47 USD/W was adopted. Furthermore, Fraunhofer Institute had estimated a price range of PV in 2050 between 0.33–0.71 USD/W [61], while International Energy Agency forecasted a price at 0.47 USD/W [62].

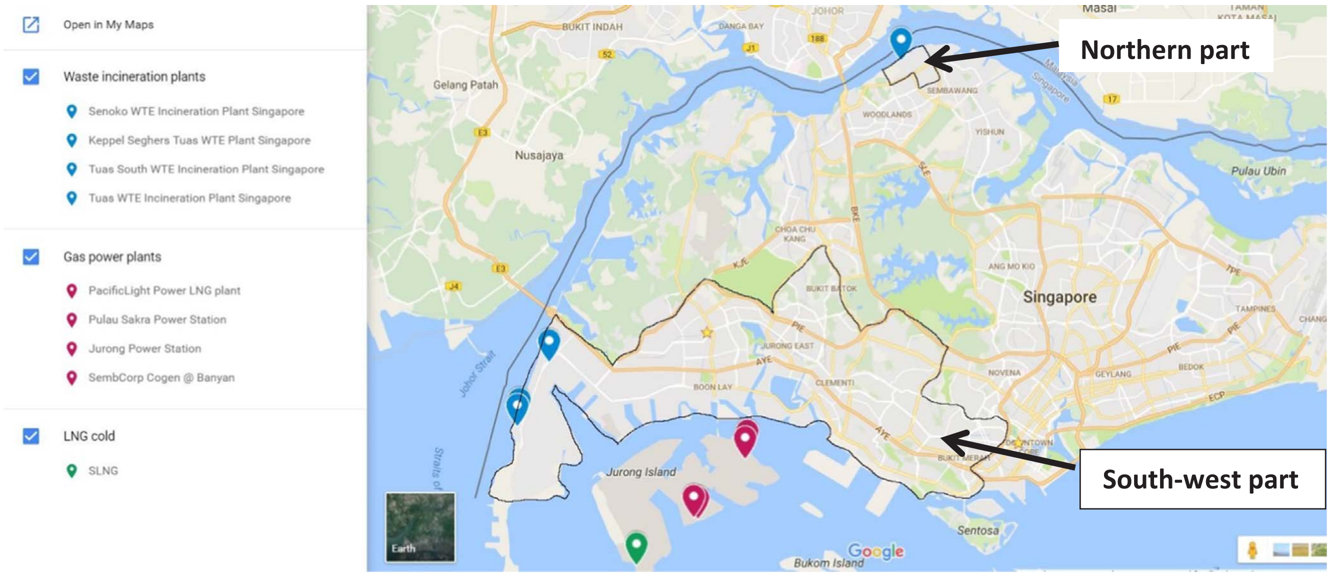

Fig. 3. Locations of major waste heat sources, cold from LNG gasification terminal and the modeled areas (designated with black boundaries) for district cooling in DC and DC-PV scenarios (Map data ©2017 Google).

PPs (as other two gas plants are already supplying waste heat to the industry), three waste incineration plants located in that part of the island and the LNG gasification terminal. It can be seen from the Table 7 that the simulated cooling energy demand E_{supply} is lower than the potential C_{supply} in the both areas. Thus, the assumed district cooling system is technically viable.

There were in total 54 transmission pipe sections and 61 distribution pipe sections modeled for the South-west part of Singapore and four transmission and five distribution sections for the northern part of Singapore (Woodlands). Resulting radii of each pipe section needed to be sufficient to transfer the sufficient amount of cooling energy, covering both thermal and mechanical losses of the grid, taking into account that the maximum possible ΔT_2 was set to 13 K.

For the northern part of Singapore, resulting transmission pipe radii were between 0.36 m and 0.71 m while the distribution pipes radii were between 0.19 m and 0.64 m. During the simulated week, the total grid losses account for 5.7% of the cold supply to the grid. Out of the total losses 19% occurred as mechanical losses and 81% as thermal losses. Changing cooling demands in different hours was met by changing temperature difference in the supply network, keeping the mass flow constant. Detailed scheme of the grid in both geographical areas can be seen in the Appendix 1, while the detailed numerical results can be assessed in the Appendix 2.

For the South-west part of Singapore, resulting transmission pipe radii were between 0.16 m and 1.94 m while the distribution pipe radii were in the range of 0.06–0.8 m. It should be noted here that pipe diameters above 0.7 m would be constructed as two or more parallel pipes instead of very large diameters of a single pipe. The total losses in the South-west part were equal to 4.76%. The share of mechanical losses was 18.3% and the share of thermal losses was 81.7%. Detailed results of piping dimensioning, thermal and mechanical losses in each hour during the modeled week and the temperature differences in each hour can be seen in detail in Appendix 2.

Table 7
Simulated weekly and calculated yearly cooling energy demand.

	C_{demand} [GWh] - weekly	C_{demand} [GWh] - yearly	E_{supply} [GWh] - weekly	E_{supply} [GWh] - yearly	C_{supply} [GWh] - yearly	Grid cost [mil USD]
Northern part	15.01	782.6	15.80	823.9	1238	8
South-west part	322.07	16793.5	338.17	17633.2	21,609	331

Overview of the main results of Appendix 2 can be seen in Table 8.

Taking into account obtained radii and length of each pipe section, using equation (15) and adopting values P_i (the cost of installing piping per unit of length, as a function of the pipe radius) from [67], the total investment in district cooling grid was calculated. The total investment cost of the northern part of Singapore amounted to 8 million USD, while the total investment cost in the South-west part of Singapore totaled to 331 million USD. These investment cost were levelized over the period of 30 years using a discount rate of 4%. Yearly operating and maintenance costs were set to 3% of the total investment.

4.2. Reference scenario and model validation

A comparison of the total primary energy supply and CO_2 emissions obtained for the reference year (2014) in EnergyPLAN modeling tool

Table 6
Calculate net usable area for PV installations.

	Area utilization factor	Conservative net-usable area from [54] [km^2]	Net usable area after population rise is taken into account [km^2]	New area utilization factor	Net usable area after less conservative approach is taken [km^2]
Rooftop area	0.5 and 0.6	34	43.83	0.9	60.23
Facades	0.4	4	5.16	0.6	7.16
Infrastructure	1	0.5	0.5		0.5
Islets	0.05	2.5	2.5		2.5
Inland waters	4	4	4		4
Total		45	56		74.4

Table 8
Overview of the results presented in Appendix 2.

	Woodlands (Northern part)	South-west part
Minimum transmission pipe radius [m]	0.365	0.164
Maximum transmission pipe radius [m]	0.716	1.943
Average transmission pipe radius [m]	0.607	1.048
Minimum distribution pipe radius [m]	0.193	0.064
Maximum distribution pipe radius [m]	0.636	0.795
Average distribution pipe radius [m]	0.341	0.309
Total weekly pressure losses [GWh]	0.18	2.95
Total weekly thermal losses [GWh]	0.75	13.16
Maximum delta T [K]	12.83	12.68
Minimum delta T [K]	0.00	1.32
Average delta T [K]	4.14	8.20

Table 9
Comparison of reference scenario in EnergyPLAN and official values.

	Reference scenario (REF)	IEA [45]	Difference
Coal consumption	4.63	4.6	0.28%
Gas consumption	109.07	106.9	1.95%
Oil consumption[a]		206.2	
Oil consumption - only combustion	85.93	82.5	4.02%
Primary Energy Supply[a]		325.8	
Primary Energy Supply (only combustion)	207.73	202.1	2.71%
CO_2 emissions	46.857	45.32	3.28%

[a] IEA includes oil consumption used in petrochemical industry for production of different products that have no accompanied CO_2 emissions. In EnergyPLAN this part of the primary energy supply is not modeled; only the primary energy demand for combustion purposes, which produce CO_2 emissions, could be modeled.

and values obtained from International Energy Agency's website for Singapore [45] can be seen in Table 9.

It can be noted from Table 9 that the difference between official data and the data obtained from the simulation do not exceed 5% for any of the fuels or CO_2 emissions. Hence, it was concluded that the model can be used for modeling future energy scenarios of Singapore.

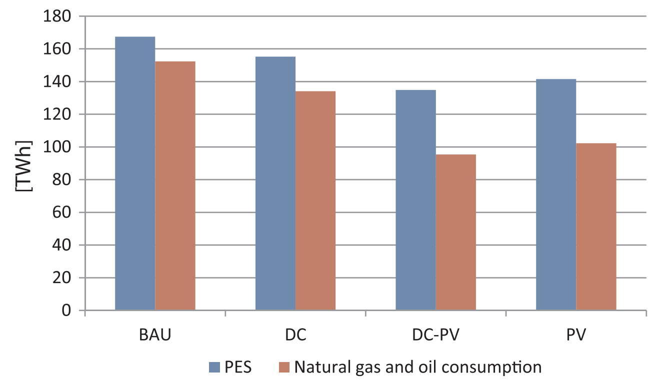

Fig. 5. Primary energy supply and fossil fuel consumption in different scenarios.

4.3. Scenarios for the year 2050

Total socio-economic costs and CO_2 emissions for the BAU and alternative scenarios for the year 2050 can be seen in Fig. 4. The largest costs occurred in BAU scenario (10,884 mil USD), followed by DC (7628 mil USD), PV (7133 mil USD) and DC-PV (6631 mil USD) scenarios. Scenarios lower in total socio-economic costs had also lower CO_2 emissions. The CO_2 emissions in BAU, DC, PV and DC-PV scenarios were 36.23, 29.06, 22.57 and 21.21 Mt, respectively. One can note also that the variable costs in the BAU scenarios are much larger than in alternative scenarios, making alternative scenarios less volatile and less prone to changes in import prices of the fuels.

The total primary energy supply and gas consumption in different scenarios can be seen in Fig. 5.

Primary energy supply in the DC and PV scenarios was 7.3% and 15.5% lower than in BAU scenario. The largest PES reduction occurred in DC-PV scenario; its PES was a significant 19.5% lower than in BAU scenario. DC-PV scenario also showed that the optimal level (that minimizes the total socio-economic cost of the energy system) of centrally installed electric chillers was 89 MW_e, and the optimal capacity of cold storage was 7.7 GWh_c. Due to the serious scarcity of land in Singapore, ice-storage was assumed to be used in order to utilize the latent heat of ice, lowering the needed volume for the storage. The ice cold storage with the capacity of 7.7 GWh_c would have a volume of 90,536 m^3.

In order to assess the behavior of selected technologies in the simulated energy system, an excerpt from the simulation results for the DC scenario is shown in Fig. 6.

It can be seen from Fig. 6 that the centralized electric chillers are operating when there is a significant generation of electricity from PVs. In that way, electricity with a low marginal cost of generation can be

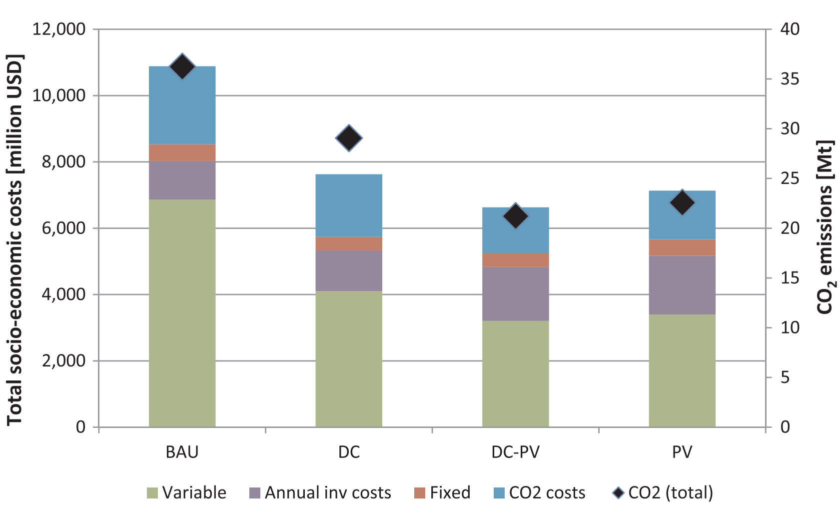

Fig. 4. Economic and environmental results of different scenarios for the year 2050.

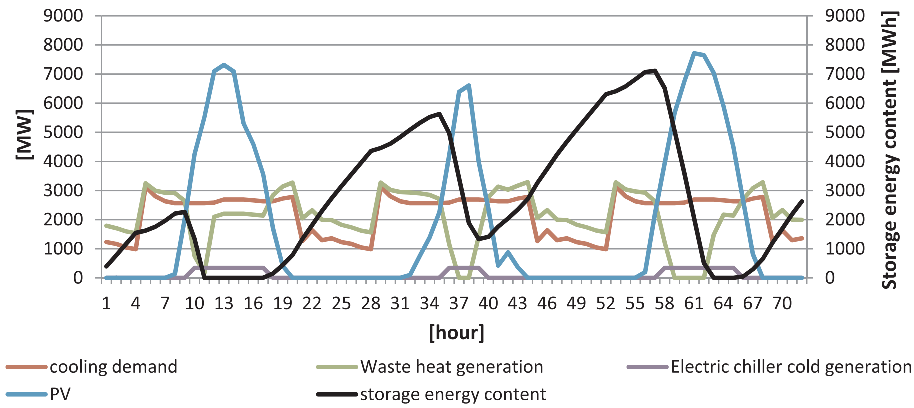

Fig. 6. Operation of different selected technologies in the DC scenario during the first three days of the year 2050.

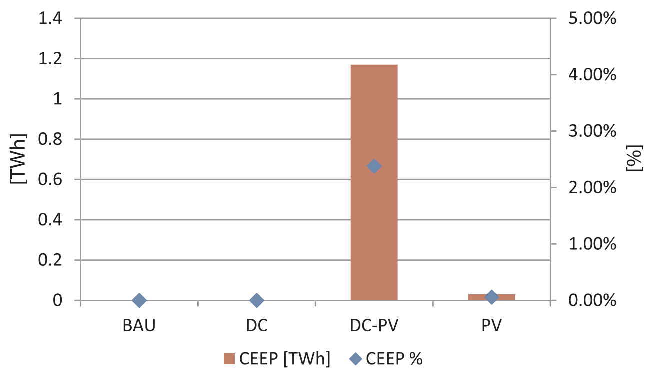

Fig. 7. CEEP in absolute and relative amounts in different scenarios for the year 2050.

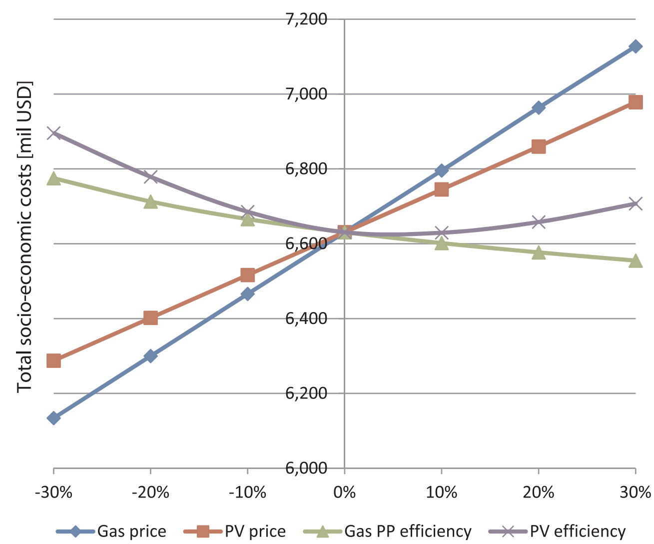

Fig. 8. The impact of different variables on total socio-economic costs.

utilized to produce cold in an efficient way, reducing also the potential of having the excess electricity generation during the peak PV output. Furthermore, it can be noted that the waste heat generation will drop during the maximum output from PVs, as PVs are able to meet the total electricity demand in those periods (and no electricity and heat generation are needed from gas CHPs and waste incineration plants). On the other hand, except the electric chillers, cold storage is the technology that can help meeting the cold demand in periods when there is a lack of waste heat generation that could be utilized in absorption chillers. In periods when there is an excess in waste heat generation, cold can be stored for later periods. In this way, cold storage, electric chillers, PVs, CHPs and waste incineration plants can successfully integrate power and heat/cold sectors, utilizing a cheaper ice cold storage compared to the battery storage.

One of the negative consequences of large share of intermittent renewable energy in the energy system is the occurrence of periods when the generated electricity exceeds the demand for it, wasting electricity that could have been generated for a low marginal cost. EnergyPLAN software introduced Critical Excess in Electricity Production parameter (CEEP). The CEEP is the amount of electricity that is generated but cannot be exported or utilized as there is not enough demand. The energy system is technically solid, and renewable energy sources are successfully integrated, if the CEEP does not exceed 5% of the total electricity generation. The CEEP indicator in both absolute and relative terms is presented in Fig. 7.

The share of CEEP was well below the 5% target, which shows that large amount of intermittent can be successfully integrated in the energy system of Singapore. Following the implementation of the assumptions presented in the Table 4, the resulting share of renewable energy sources in power generation was 70.6% in DC-PV and 64.8% in PV scenarios. A successful integration of these large amounts of intermittent renewables was possible due to the electrification of a part of the transport and utilizing the V2G concept, as well as the utilization of cold storage that is cheaper compared to battery storage. By combining the electric chillers in the periods of low demand and/or high electricity generation, one can produce cold and store it in the cold storage for later use in the district cooling network.

4.4. Sensitivity analysis

In order to check the robustness of the results, a sensitivity analysis was carried out. The analysis was carried out for DC-PV scenario and the influences of gas price, PV panels price, gas PP efficiency and PV efficiency on the total socio-economic costs and CO_2 emissions were assessed. The impact of the four mentioned variables on the total socio-economic costs can be seen in Fig. 8. One can note that the gas price has the most significant impact on the total socio-economic costs, i.e., an increase of gas price of 30% will increase the total socio-economic costs for 7.5%. An increase in the price of PV panels of 30% will result in a 5.2% larger total socio-economic cost. Very interesting behavior can be seen in PV efficiency variable. As a land in Singapore is scarce, there is a fixed amount of space where PV panels can be installed. Having lower efficiency than expected, less capacity of panels will be possible to install, which causes larger total socio-economic costs because of the more fossil fuel demand. On the other hand, exceeding the panel efficiency by more than 10% will also cause larger total socio-economic costs. The latter can be explained by already large share of the electricity generated from the PV in the DC-PV scenario. Further increase in the installed PV panels causes more and more excess electricity generation which cannot be consumed and thus, installation costs of additional PVs cannot be recuperated by savings in fossil fuel and CO_2 payments.

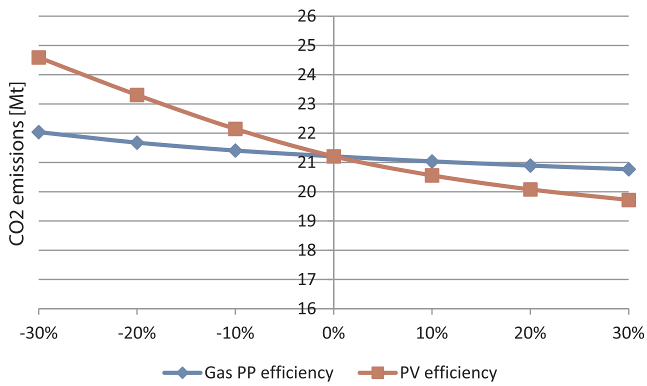

Fig. 9. The impact of different variables on total CO_2 emissions.

The impact of gas PP efficiency and PV efficiency on the CO_2 emitted can be seen in Fig. 9. PV efficiency has much larger influence than the gas PP efficiency and the decrease of 30% in PV efficiency would increase CO_2 emissions for 15.9%.

On the other hand, the increase of PV efficiency for 30% would result in 7.02% lower CO_2 emissions. The latter is caused by already large penetration of electricity generated from PVs and a large share of the additionally generated electricity would not be consumed (the PV production would be curbed) due to the mismatch in timing of electricity generation and demand. Relatively low reduction of CO_2 emissions in the case of 30% larger gas PP efficiency, i.e. 2.1% lower CO_2 emissions, is mainly the result of low generation share of electricity generated from gas driven plants in DC-PV scenario, i.e. 29.4%.

5. Discussion

The results of this paper show that there is a significant potential of waste heat that can be utilized via absorption chillers to produce cold. However, due to the nature of the sources, which are highly concentrated at few sites, a district cooling network needs to be established in order to connect the customers demanding the cooling energy with energy sources. The resulting calculation of the district cooling grid showed that the total investment of 339 million USD is offset by total socio-economic savings, making the potential future energy system of Singapore cheaper, more energy efficient and less climate harmful. The CO_2 emissions in DC-PV scenarios were 41.5% lower compared to the BAU scenario, while the total socio-economic costs were lower by 39.1%, achieved mainly by significantly reduced import of fossil fuels. Imports of gas and oil in DC-PV scenario were 37.4% lower than in BAU scenario. The latter shows that implementation of district cooling, along with the PVs, can increase the security of energy supply by reduction of import energy demand. It is interesting finding that scenarios lower in total socio-economic costs have also lower CO_2 emissions. This means that the savings in fuel costs and carbon tax payments offset the additional investment costs in the energy infrastructure.

Introducing district cooling network removes the need for having many decentralized cooling towers, usually located on the rooftops, allowing more PVs to be installed on the rooftops. Already high renewable energy share in power generation of 64.8% in the PV scenario increased even more, to 70.6% in the DC-PV scenario, while still achieving technically sound system, with CEEP indicator being significantly below the threshold of 5%.

After reaching a large share of intermittent renewable power in the energy system, further penetration of it needs to be balanced by energy storage. As there are no hills in Singapore that would be suitable for pumped hydro plant, one option could be to install electric batteries for storing the excess electricity generated. However, a cheaper option is to utilize cold storage and electric chillers in periods when there is excess of cheap electricity generated. The result of utilizing the latter combination is that the costs in DC-PV scenarios were 7.0% lower than in PV scenario, although investments in cold storage and central electric chillers had to be taken into account.

Moreover, although it was not a subject of this paper, removing decentralized cooling towers from the densely populated areas of the city reduces the heat island effect. However, to quantify this benefit, a more detailed study should be carried out.

Compared to the more systematic studies carried out mostly in Europe, and presented in the Introduction section, a significant difference that occurs in the energy system of Singapore is the lack of any kind of energy potential, i.e., the temperature difference of the air, ground and sea is very uniform during the year and there are no mountains that could be utilized for pumped hydro storage. Hence, no free cooling sources could be utilized in this area. On the positive side, relatively steady and high temperature and humidity over the year result in a constant cooling energy demand.

Further focusing on the case study, it can be also used to support Singapore's Research, Innovation and Enterprise 2020 Plan [69]. One of the domains of the mentioned plan is the Urban Solutions and Sustainability (USS) in which it is stated that one focus to accelerate the translation of R & D to industry adoption will be Waste to Energy plant in Tuas. The findings presented in this paper about the potential for district cooling can further steer the research for successful utilization of the waste heat from Waste to Energy plants located in Singapore. However, it must be noted that the non-homogeneous operations of the Waste to Energy plants coupled with the variability of the waste heat available might affect the amount of chilled water generated by the absorption chillers; this aspect should be carefully assessed when sizing and designing the district cooling system.

Future work could further integrate water sector into holistic planning of the energy system, especially as Singapore currently uses reverse osmosis technology for water desalination that satisfies one part of the water demand of Singapore. Reverse osmosis desalination is a suitable technology for demand response measures that could further integrate intermittent renewable energy sources such as photovoltaics. Possible benefits of integration of reverse osmosis in the energy planning was presented in [65].

Finally, this study successfully showed that the implementation of district cooling system in hot and humid climate is economically sound, environmentally beneficial and a technically viable investment. Compared to the other studies presented in the Introduction section, this paper successfully quantified both costs and benefits of installing a district cooling grid, as well as its impact on the holistically modeled energy system. Finally, both thermal and mechanical losses were calculated for the proposed layout of the transmission and distribution grid. A future research should further address the concept of smart energy system, integration of different areas within the city and implementation of enhanced ICT technologies in DC systems that could introduce additional flexibility and demand response in the energy system.

6. Conclusions

There are three main conclusions that arose from the case study, which showed that district cooling systems in hot and humid climates are beneficial solution, especially in future energy systems, dominated by large shares of intermittent renewable energy sources. First, there are significant environmental benefits as the consequence of integration of district cooling in the energy system. The CO_2 emissions of Singapore's energy system were lowered by 41.5% in the year 2050 in the DC-PV scenario compared to the BAU scenario. The beneficial scenario assumed the implementation of district cooling, increased penetration of PVs, improved energy efficiency in industry and buildings and the implementation of smart charge of vehicles. Second, implementation of district cooling significantly raises efficiency of the energy system. The primary energy supply in PV and DC-PV scenarios were 15.5% and 19.5% lower than in the BAU scenario for the year 2050. Third, implementation of district cooling can positively impact the economic side of the energy system. The total calculated investment cost in district cooling grid amounted to 339 million USD. However this cost was offset by increased energy savings in terms of fossil fuel imports. Thus, the total socio-economic costs of the energy system of Singapore in DC and DC-PV scenarios were 32.7% and 38.4% lower than in BAU scenario. Sensitivity analysis showed that the results are generally robust, while the largest influence on the total socio-economic costs had natural gas price. Concerning the CO_2 emissions, the most sensitive parameter is the anticipated efficiency of PV panels.

Compared to other studies on district cooling, this study focused on district cooling on a system scale, developing a detailed model of transmission and distribution grid feasibility. Hence, the developed model is well suited for other district cooling systems in the region. The latter could be very significant as south-east Asia is rapidly developing region, with estimated growth in energy demand of 80% until the year 2040 [4]. Having well financed R & D programs, and being economically developed country, Singapore could be a role model for implementation of district cooling systems on a large scale, as well as facilitate knowledge transfer towards other countries in the region. Finally, systematic development of district cooling grid before rapid development takes place can be beneficial measure for increasing energy efficiency of the system, as well as improve the economic feasibility of implementing the district cooling system.

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Appendices 1 and 2. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.09.052.

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